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## TESTING OF AN INDUSTRIAL ROBOT'S ACCURACY AND REPEATABILITY IN OFF AND ONLINE ENVIRONMENT

### BADANIA DOKŁADNOŚCI I POWTARZALNOŚCI POZYCJONOWANIA ROBOTA PRZEMYSŁOWEGO W ŚRODOWISKACH OFF I ONLINE\*

*The paper discusses issues concerning the accuracy and repeatability tests of the positioning of the Kuka KR 16-2 industrial robot. The results of laboratory tests of an industrial robot, as well as a comparison of robot motion paths in the Robcad environment with the real robot motion paths are presented. In order to register movement paths in the laboratory conditions, the laser tracker Faro Vantage was used. Frequent necessity to correct programs of industrial robots created in the offline environment, is a results, among others, from the insufficient experience of people who carry out programming, the environment in which robots work and the parameters of the robots themselves, and therefore their accuracy and repeatability. It is connected with the extension of the start-up time and high costs. The work describes the measurement method and attempts to determine the influence of the type of route and motion parameters on the accuracy and repeatability of robot. The accuracy of mapping of simulated robot motion in a virtual environment was also verified.*

**Keywords:** industrial robot, offline programming, online programming, positioning accuracy, repeatability of positioning.

*W pracy omówiono zagadnienia dotyczące badań dokładności i powtarzalności pozycjonowania robota przemysłowego Kuka KR 16-2. Przedstawiono wyniki badań laboratoryjnych robota przemysłowego, a także dokonano porównania ścieżek ruchu robota symulowanego w środowisku Robcad ze ścieżkami ruchu robota rzeczywistego. W celu rejestracji ścieżek ruchu w warunkach laboratoryjnych zastosowano laserowy tracker Faro Vantage. Często konieczność poprawy programów robotów przemysłowych utworzonych w środowisku offline wiąże się z wydłużeniem czasu uruchomienia i dużymi kosztami. W artykule opisano metodę pomiarów oraz podjęto próbę określenia wpływu rodzaju ścieżki dojazdu do punktów pomiarowych i parametrów ruchu na dokładność i powtarzalność pozycjonowania robota. Zweryfikowano także dokładność odwzorowania ruchu robota symulowanego w środowisku wirtualnym.*

**Słowa kluczowe:** robot przemysłowy, programowanie offline, programowanie online, dokładność pozycjonowania, powtarzalność pozycjonowania.

#### 1. Accuracy, repeatability and programming of the movement of industrial robots

In modern industrial plants, robotic production cells and industrial robots are an extremely important element. In order to achieve the maximum efficiency and reliability of automated and robotic production lines, numerous scientific studies are carried out aimed at both the development of technical means themselves, as well as methods for their programming and exploitation [1, 2, 4, 5, 8, 10, 11, 13, 18]. In the case of industrial robots, the accuracy and repeatability of positioning are extremely important features affecting their operation [3, 6, 7, 12, 19, 21, 22, 26]. Therefore, research is conducted to improve the existing state of operation of this type of technical means, as well as to improve the measurement methods of their parameters [7, 9, 14-17, 20, 23, 24].

The accuracy of the manipulator is called his ability to reach a given point in the workspace. The basic method of determining accuracy errors in the positioning of an industrial robot is to measure angular or linear changes in individual links of its manipulator [19-21, 27, 28]. Due to the high cost and sensitivity for interferences of the used sensors, methods of direct measurement of the end effector are used less frequently. The factors of accuracy of positioning are influenced

by factors described more widely, among others, at work [21], such as positioning errors and trajectory rendering (for example due to deformations caused by the temperature, inaccuracies of control system signals or inertial forces). According to the PN-ISO 9283 standard, the accuracy of unidirectional positioning (AP) describes the deviation between the set position and the average value of the actual positions when reaching the set position from the same direction [26]. Repeatability of the manipulator is the ability to move the effector tip to the same, set point in space. The resolution of the control system is the first to influence the reproducibility of the manipulator.

Manipulators of industrial robots, currently used in industry, are characterized by very good reproducibility (RP) but not very good accuracy (AP). The measurement of the manipulator's position in the basic configuration is most often carried out by reading data from an encoder or resolver placed on the drive shaft of each axis. Robots can be equipped with additional measuring systems, but usually this option is additionally payable. Therefore, most often the position of the tool is calculated based on the measurement of angles or offsets of joints with additional consideration of the manipulator geometry and stiffness in relation to the mass it carries (tool load). The positioning accuracy is influenced by the loose (wear) in joint connections, friction, transmission errors in gears, accuracy of the manipulator elements,

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finite mechanical stiffness, computational errors, work environment, elastic effects of components and mounting method, as well as many other static and dynamic factors.

Unfortunately, most of the above factors are subject to constant changes that cannot be predicted, which lead to the creation of differences between mathematical models and real characteristics. These differences can be tried to reduce by recalibrating mathematical models. Another method of improving accuracy can be the use of direct sensors at the end of the robot's mechanical interface, for example laser, inductive and vision sensors.

The most common method is programming robots through teaching. This method consists of discrete programming and continuous programming, which are very different by the character of teaching. Discrete programming is mainly used for manipulation of objects, for gluing and welding, and continuous programming is used where the movements of the robot must be smooth and continuous. This type of programming is very well suited to applications such as spray painting.

Currently, the offline robot programming method is being intensively developed. Its use gives the opportunity to significantly reduce costs, such as the cost of introduction of a new car model for production on the production line. In this method, the robot or its surroundings are very little needed for the programming process itself. It runs in a simulated 3D environment using Robcad, Delmia, Roboguide, Robot Studio, or Process Simulate software. The created virtual environment includes 3D models of devices from the existing technological line, the location of which is faithfully reproduced by 3D laser metrology, which allows for very accurate programming of robots, without the need for their physical participation. This action allows shortening the start-up time, reduces costs and allows for better refinement of the cycle time of the production line. A quick response is also possible when one of the models is incompatible, for example when the gripper is incompatible with the manipulation object at a given production stage. An additional advantage of this method is to reduce the risk of accidents on the assembly hall and increase the safety of robot operators. In offline programming, the precision of mapping of real objects as well as the robot itself is very important, taking into account the parameters of its work, including the accuracy and repeatability of positioning. Any errors in this regard are connected with the necessity to verify and improve the program developed in the real environment. This significantly reduces the advantages resulting from the offline robot programming method.

## 2. Research and methods to verify and improve the characteristics of industrial robot move

In this paper, attempts have been made to examine and verify the accuracy and repeatability of the positioning of an industrial robot simulated in a computer environment and a real robot. In order to carry out the tests, a laser measuring device was used. In [24], the authors also presented the concept of a method for measuring accuracy and repeatability using laser measuring technology. The use of detection based on laser interferometry, in the proposed technique of estimating positioning errors, aimed at improving the accuracy of an industrial robot, is also presented in [9]. This method is also presented in the works of other authors, in which precise, laser measuring devices are proposed as tools for positioning manipulators of industrial robots and machines [12, 14, 20].

Repeatability of the robot is limited mainly by the resolution of the position reading system, i.e. the smallest value that this system can recognize. Linear axes, so prismatic joints, usually have a better resolution than rotary axes (in a comparable price class), because the straight line drawn between two points is shorter than the corresponding arc. Spong and Vidyasagar [22] proved that in rotary axes errors are cumulated and are greater than in linear axes and result

from stronger kinematic and dynamic couplings in these drives. This leads to increasing problems with controlling these axes. Another error hierarchy is described in [25]. It is as follows: position of the TCP (Tool Center Point), work piece position, joint position calibration, shoulder length and angular errors, shoulder flexibility, position encoder resolution, clearance, flexibility and misalignment, thermal deformation. The work [25] also discusses in detail the division and percentage share of the impact of individual error sources on the accuracy and repeatability of positioning. The presented data show that the most important impact on the accuracy of the robot is its incorrect calibration. Therefore, proper calibration is a condition that must be kept at the beginning of each work with an industrial robot. The ability to quickly and accurately calibrate is also an intensively developed issue in the aspect of building robots and their equipment [25].

In the article [26], the authors emphasize that the main disadvantage of programming robots in offline mode is their low accuracy. They indicate that industrial robots are mainly programmed using methods that only require good repeatability. As a result, little is done to improve parameters regarding the accuracy of positioning of industrial robots. The authors of the discussed study conducted experimental research on three modern robots in order to evaluate and compare their positioning accuracy. Based on measurements using a laser interferometry system, the accuracy errors of each robot were measured and the obtained results were compared. As it was demonstrated by the authors, analyzing the obtained results, it can be stated that in comparison to older robot models, the positioning accuracy of modern industrial robots can be very good, but achieving such accuracy depends on the correct calibration process.

Paper [21] presents the results of an experiment to assess the accuracy and repeatability of an articulated industrial robot. Six factors were analyzed, which are most often indicated as affecting the parameters of its work. The object investigated was the Fanuc M16iL industrial robot. The planning, carrying out tests and analysis of the obtained results were described in detail. The verification of the accuracy and repeatability of the robot given by the manufacturer was also presented.

In work [16], the effectiveness of a measuring device designed for absolute calibration of small industrial robots was experimentally demonstrated. The proposed method of calibration is manual and labour-intensive, but its implementation takes less than an hour, and the cost of the measuring device used is less than 13,000 USD. As the authors of the study [16] indicate, the mean values and standard deviation of the absolute position and distance errors would then be about three times smaller. They proved that when the calibration time is not a problem, various improvements to the proposed solution are possible. Calibration, for example, can be repeated at different positions of the basic device. Different calibration models can also be used in different work zones. It is also possible to extend the proposed measurement system, and thus extend the range of measurable robot configurations four times. The authors suggest that the proposed calibration procedure has enormous potential as it is cheaper compared to the absolute calibration of small industrial robots. It can also be additionally used to confirm the accuracy of robot positioning. In another study [17], the authors proposed a 29-parameter calibration model and a procedure for the identification of the parameters of this model and measurements of an industrial robot ABB IRB 1600-6/1.45. This application makes it possible to improve the accuracy of the robot in terms of average and maximum position errors in the entire working area. The authors admit that the better effectiveness of the proposed method cannot be demonstrated juxtaposing with other calibration methods, including the method proposed by the robot manufacturer, however, the results obtained can be used as a reference point for comparative analysis.

Also in [15] the authors point out that one of the problems slowing down the development of offline programming is the low static and

dynamic accuracy of positioning of industrial robots. They indicate that the correct calibration of the robot improves the accuracy of its positioning and can also be used as a diagnostic tool in the manufacture and maintenance of robots. They present modelling techniques and performing robot calibration processes in offline programming mode using a three-dimensional measurement system. The authors indicate that the proposed measurement system is portable, accurate and not expensive. The discussed solution consists of a single CCD camera mounted on the robot's tool collar, which aims to measure the position of the end effector relative to the global coordinate system. In this photogrammetric model, radial distortion was taken into account. Scaling factors and image centres were obtained using an innovative technique with a multi-view approach. Achievable average accuracy was from 0.2 to 0.4 mm at distances from 600 to 1000 mm from the target, respectively in different camera orientations. The authors present the results of experiments carried out by two industrial robots ABB IRB-2400 and PUMA-500 in order to show the improvement of their accuracy using the proposed calibration system. Robots after calibration achieved better accuracy (three to six times than before calibration), and the solution proposed by the authors is quick, accurate and easy to configure.

An article [7] presents a simple and less expensive method of calibrating industrial robots using a vision system. In this system, the camera is rigidly attached to the robot's bunch, recording during the work the images of the calibration plate in the form of a chessboard. The algorithm of automatic image recognition and self-calibration of the camera is used without knowing the position of the calibration plate. The authors showed that the proposed method is simpler and cheaper than standard ones. It can also be used while the robot is operating in an unknown environment and in conditions that can significantly affect the operating parameters (high temperature or pressure). It can also be used in mobile robots.

Issues to improve the accuracy of positioning of industrial robots are discussed in paper [23], in which the authors examine the possibility of using the Leap Motion Controller for this purpose, which is typically used to manually control user gestures with declared accuracy below the millimetre. The article presents the study of the motion controller and the main emphasis is on the evaluation of its accuracy and repeatability. A test stand with the use of an industrial robot equipped with a reference pen to measure position accuracy up to 0.2 mm was developed. In the conducted experiments, a deviation was obtained between the desired position of the robot and its mean measured position, less than 0.2 mm in the case of static systems and 1.2 mm in the case of dynamic configurations.

The mentioned scientific publications are only selected items from the extensive, accessible literature on the subject. They confirm that there are numerous studies on both measurement methods and solutions that improve the accuracy and repeatability of positioning of industrial robots. In most studies, the correct calibration of an industrial robot is indicated as a factor significantly affecting these parameters. Various methods of measuring and improving the precision of mapping of programmed paths of industrial robot movements are also proposed. In this study, the authors also attempted to verify the accuracy and repeatability of the positioning of the selected industrial robot using a laser measuring system. Moreover, a comparison of the obtained values with the results obtained in a virtual simulation environment is presented, which is important in the offline programming of industrial robots.

The aim of the work carried out and discussed in the article was to propose a method for testing the accuracy and repeatability of industrial robot positioning in accordance with PN-EN 9283, using a standard tool that was used so far by people programming robots to measure a robotic cell and its modelling in a virtual environment. This topic is extremely important for people involved in programming industrial robots due to frequent discrepancies between the robot's motion path

simulated in a virtual environment and the real robot motion path, performed on the basis of a program written in the offline environment. These discrepancies cause the necessity to make adjustments to programs before starting the work of robots and are associated with high time-consuming work, as well as with high costs.

### 3. Simulation and experimental tests of an industrial robot

This paper presents the results of simulation tests and laboratory measurements of a real object - the robot Kuka KR 16-2. The type of industrial robot under consideration is mainly used for welding tasks (it has a lifting capacity of 16 kg and its own weight of 235 kg).

In order to compare the results of offline and online programming, data generated in both the Robcad program and by the Faro Vantage laser tracker, used in measurements on the real object, were used. In the Robcad program was written, tested and loaded into the type of robot under consideration. In the simulation were used tools from groups:

- Motion that allows manipulating the simulated robot;
- Kuka KR C1 Spot, responsible for operating the Robot Controller Software (RCS) and entering information about individual points;
- Path Editor, where information about saved robot paths is stored;
- Placement Editor, responsible for the ability to move objects in a robotic cell.

In order to be able to use the Faro tracker for measurements during the conducted tests, it was necessary to properly determine the base (work object) and the Tool Center Point (TCP) point of the robot, because the points created by the robot are determined by the distance and rotation of the TCP system relative to the specified base system. The robot base was defined by measurements of two planes: the first one, in order to determine the height at which the point zero is located and direction of the Z axis and the second to determine the direction of the X axis. To facilitate the work and obtain maximum accuracy, the tracker was based on the so-called robot zero point. It is a factory-defined, fixed coordinate system, placed in the central part of the J1 axis, at ground level. The TCP system was defined by attaching to the robot's load an adapter with a strong magnet and a measuring probe, and then the robot reached random eight points. Next, the coordinates of each point indicated by the robot were entered into the Kuka Funke program, with the use of which TCP values were determined. These values were written in the memory of the real and simulated robots. The values that define the TCP system are its distances and rotations relative to the tool 0 system. It is a predefined coordinate system, located in the central part of the J6 axis, at the level of the robot bunch, constantly moving with it. After measuring the TCP value (in this case it is the central part of the probe's mirrors attached to the adapter), the values are stored in the robot's memory as tool 5 and from now both the adapter and the Faro measuring device must remain immobilized on their positions (adapter was immobilized on the robot's load with the glue). The probe can be detached from the adapter for the time the robot travels with the maximum speed between points, because the adapter is very accurate and does not introduce significant measurement errors. Fig. 1 shows the considered industrial robot simulated in the Robcad program together with the TCP and Toolframe coordinate systems.

The measurements were carried out in the ProPoint SP. Z O.O. SP. K. laboratory. The required measurement conditions were provided, as a rigid, reinforced concrete base, to which the tested industrial robot manipulator was attached. The rigid substrate does not introduce significant measurement errors by, for example, bending during the robot's work. The Faro Vantage tracker was placed two meters

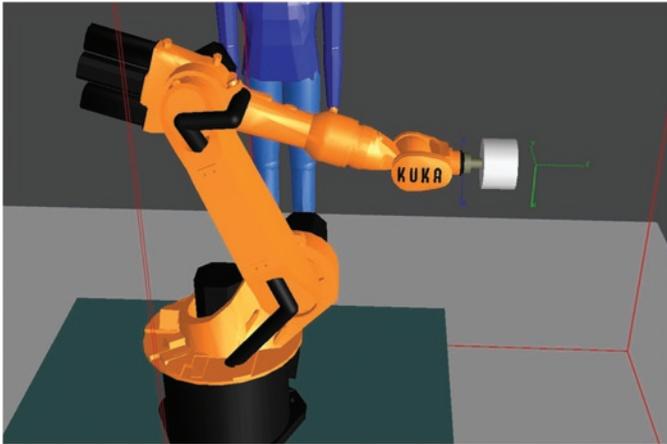


Fig. 1. Location of coordinate systems of a simulated industrial robot in the Robcad program: TCP (marked in green) and the factory defined Toolframe coordinate system (marked in blue)

from the tested robot when it is in the Home position. According to the manufacturer's specification, the accuracy of measurements performed in this configuration, when measuring the linear distance, is 0.009 mm [28]. At the end of the robot's manipulator, a load and SMR (Spherically Mounted Retroreflector) probe with the adapter was mounted, attached to the robot's bunch. The room temperature during the tests was 22 degrees Celsius (according to PN-EN 9283, a temperature of 20 degrees Celsius  $\pm$  2 degrees is required [27]). The robot was subjected to a forty-minute cycle of work on all axes before measurements, which ensured heating of drives and transmissions. The Faro tracker was immobilized in the correct position using glue. In addition, four adapters, identical to the adapter attached to the robot load, were used and were attached to stationary, metal points of the laboratory, such as a door frame. Using the base points created in this way, it was possible to re-base the measurement tracker in the event of its possible move during the tests. This operation also allows moving the tracker to a different location, because after it has been properly positioned, it is not necessary to re-determine the robot base for which measurements are made. According to the requirements, in order to ensure the reliability of measurements, they should be carried out with the full nominal load of the tested robot. Using data obtained from the Kuka Load program, the mass fixed on the J6 axis and the moments of inertia and force generated by it were determined. The load was made in the form of laser cut five steel discs with a diameter of 155 mm connected to each other which were attached to the robot's bunch using a developed adapter.

Tests that was carried out:

- accuracy of the robot, defined as the difference between the programmed and the actual coordinates of the TCP point,
- robot repeatability, that is the calculation of the sphere radius, in which the measuring points are contained during subsequent movements of the robot,
- path mapping, comparing the trajectory of the virtual robot simulated in the software and the trajectory of the real robot,
- emergency stop (E-STOP).

Guided by the recommendations included in the PN-EN 9283 standard, measuring cubes with different side lengths were determined, and the measuring points were placed in four vertices of these cubes, diagonally. The measuring plane created in this way is shown in Fig. 2 [27].

Fig. 3 and 4 show the robot in simulated and real environments, at measurement points selected from C4-C3-C6-C5 (Figure 2). This comparison allows specifying the robot's configuration and determining if it is the same in both environments. Analyzing the obtained results, it can be stated that the robot in the simulation achieves the same axis configurations as the robot in reality. These configurations

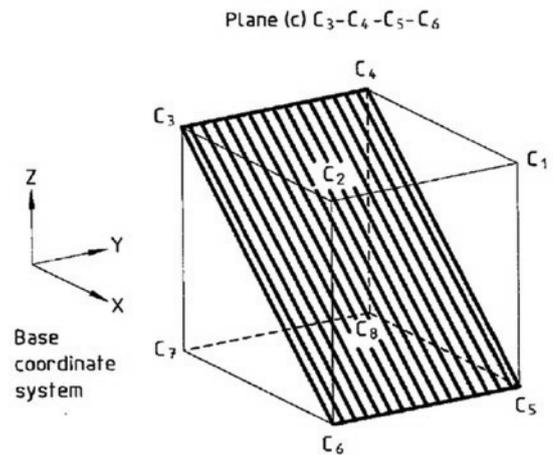


Fig. 2. Measuring plane determined by points located in the vertices of the cube in accordance with the PN-EN 9283 standard [27]

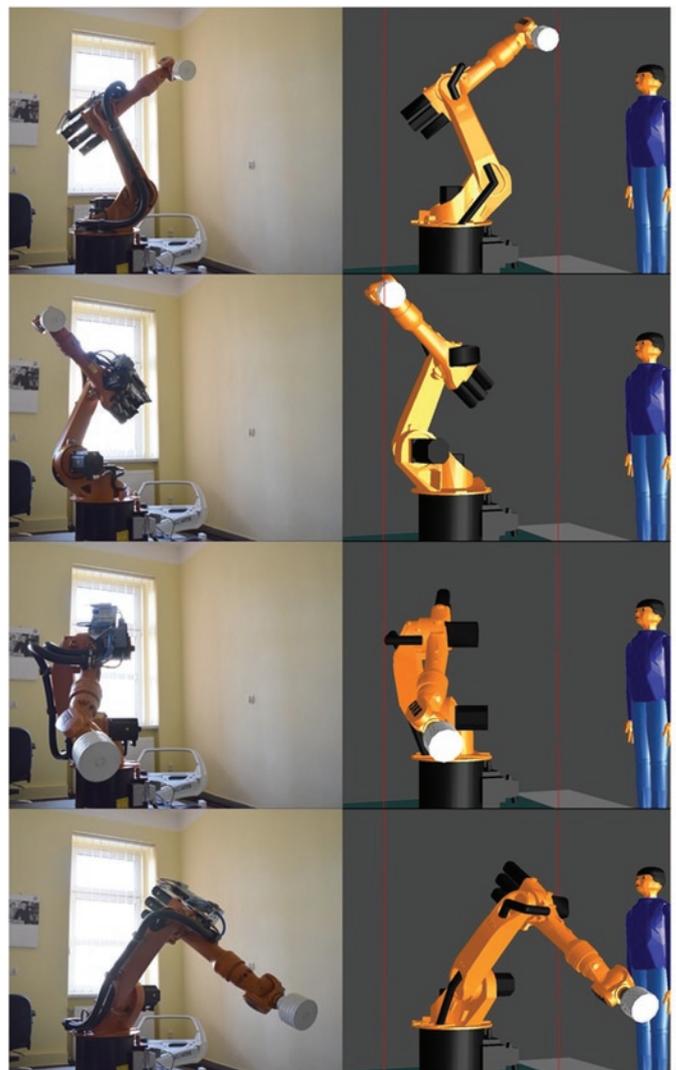


Fig. 3. Virtual and real robot at C4-C3-C6-C5 measurement points of the cube with 1000 mm side length, with tool rotation  $+20^\circ$  in Y axis

occur in simulation in several different variants, so it was necessary to recognize what option to use in the case of a real robot. This is not a problem when programming using the RCS (Robot Controller Software) system, because then it is automatically selected or converted to the correct variant. Correct projection of the real robot in a virtual

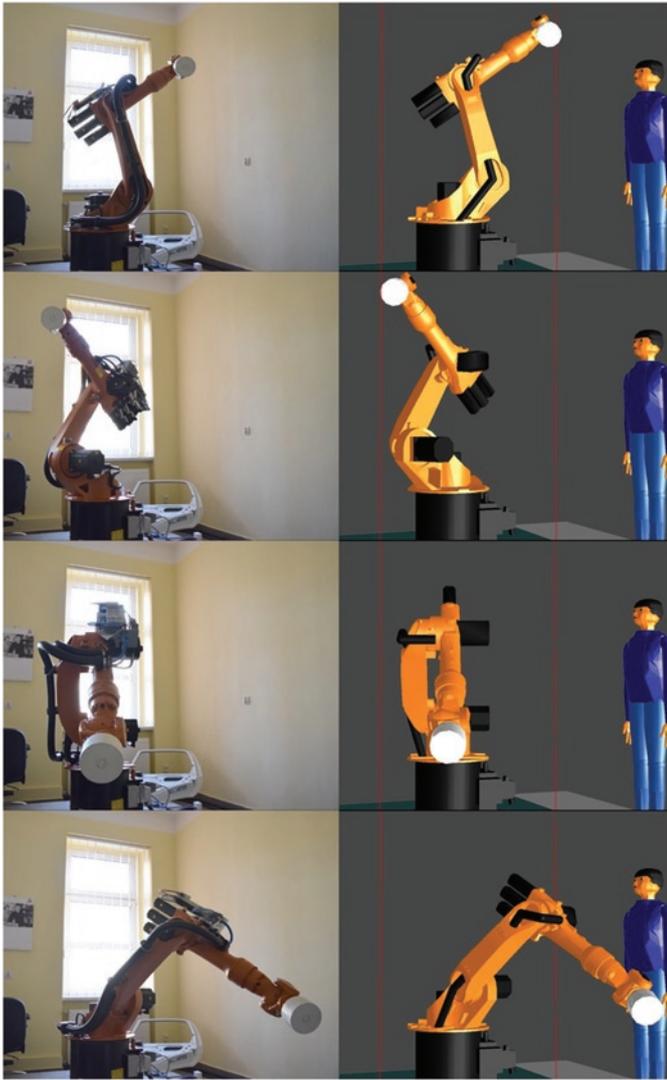


Fig. 4. Virtual and real robot at C4-C3-C6-C5 measurement points of the cube with 1000 mm side length, with tool rotation +20° in the X and Y axes

environment was found. In both presented cases, the robot is correctly projected at all measuring points. The selected two robot configurations were presented during measurements carried out in a cube with a side of 1000 mm. In the first one, the tool rotation by the angle of +20° in the Y axis (Fig. 3) and in the second the tool rotation by an angle of +20° in the X and Y axes was applied. Despite the identical C5 point coordinates, the entered tool rotation in the X and Y axes caused a change of the robot's configuration and rotation of the J4 axis by 180° in relation to the robot's configuration with the tool rotation only in the Y-axis. Both cases, however, were faithfully reproduced by the robot simulated in a virtual environment.

#### 4. Positioning accuracy tests

The positioning accuracy tests at individual measurement points marked with AP were carried out in accordance with the guidelines of PN-EN 9283 [27]. The coordinates of the set position were specified in the robot program, while the coordinates of the position reached were read from the Faro tracker's indications. For calculations the equation was used [27]:

$$AP_p = \sqrt{(\bar{x} - x_c)^2 + (\bar{y} - y_c)^2 + (\bar{z} - z_c)^2} \quad (1)$$

where:

$$\bar{x} = \frac{1}{n} \sum_{j=1}^n x_j, \quad (2)$$

$$\bar{y} = \frac{1}{n} \sum_{j=1}^n y_j, \quad (3)$$

$$\bar{z} = \frac{1}{n} \sum_{j=1}^n z_j. \quad (4)$$

The symbols  $\bar{x}$ ,  $\bar{y}$ ,  $\bar{z}$  indicate coordinates of the set of measurement points,  $x_c$ ,  $y_c$ ,  $z_c$  coordinates of the set position,  $x_j$ ,  $y_j$ ,  $z_j$  coordinates of the  $j^{\text{th}}$  measured position.

A sample of results of the robot positioning accuracy test for cubes with sides length of 200, 600 and 1000 mm, without tool rotation, are shown in Fig. 5-7. According to the guidelines included in the PN-EN 9283 standard, 30 measurements were carried out. Due to the repetitive nature of the obtained results and to ensure the readability of their presentation, the results of ten randomly chosen measurements were presented. Fig. 8 presents average results of positioning accuracy measurements at four measuring points of cubes with sides' length of 200, 600 and 1000 mm. In individual measurements, points were achieved after different robot motion paths:

- without tool rotation,
- with tool rotation by an angle of +20° in the Y axis,
- with tool rotation by an angle of +20° in the X and Y axis,
- in the case of a cube with a side length of 1000 mm, additionally without the rotation of the tool, at speeds of 10% and 50% of the maximum speed.

In the case of a cube with a side length of 200 mm, the positioning errors were in individual points: C4 (APp1) 1.23 - 1.59 mm, C3 (APp2) 1.11 - 1.53 mm, C5 (APp3) 0.8 - 0.91 mm and C6 (APp4)

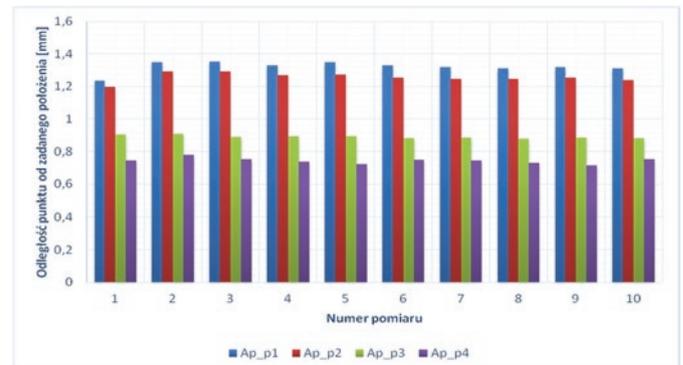


Fig. 5. Accuracy of positioning of the cube points with a side length of 200 mm, without tool rotation

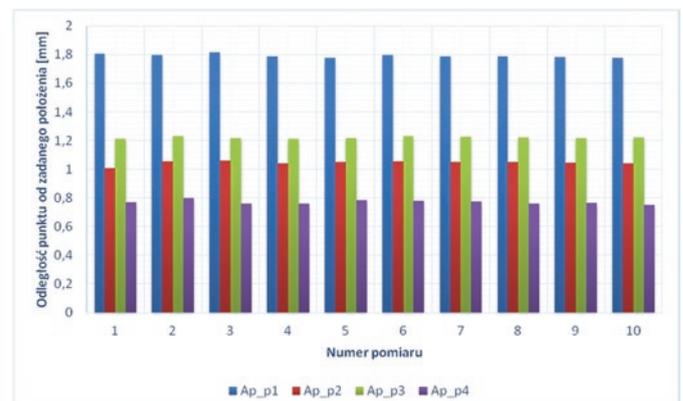


Fig. 6. Accuracy of positioning of the cube points with 600 mm side length, without tool rotation

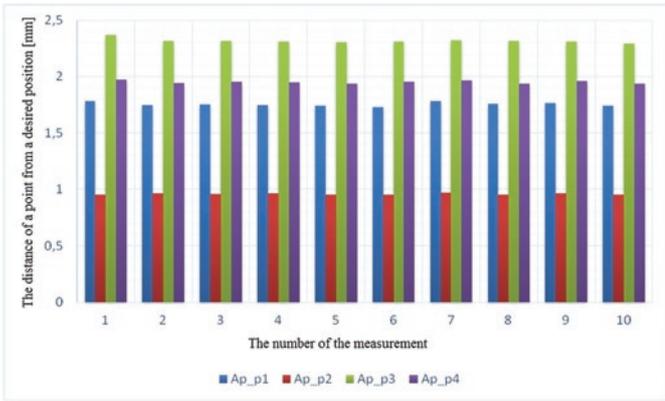


Fig. 7. Accuracy of positioning of cube points with 1000 mm side length, without tool rotation

0.74 - 1.1 mm. Significant fluctuations in the positioning accuracy were found in the case of the C4 point, which may be due to the fact that the robot was approaching this position from the Home point located in the centre of the measurement cube. The results of the positioning accuracy test for a cube with 600 mm side length showed the following positioning errors at individual points: C4 (APp1) 1.74 - 1.81 mm, C3 (APp2) 1.13 - 1.6 mm, C5 (APp3) 0.87 - 1.22 mm and C6 (APp4) 0.54 - 0.77 mm. At point C6, the robot is therefore characterized by a very high positioning accuracy, which does not require the use of additional corrective measures in the event of application of the developed program in the industry. When measuring the positioning accuracy of the robot in a cube with a side length of 1000 mm, it was found at individual points the following positioning errors: C4 (APp1) 1.5 - 1.77 mm, C3 (APp2) 0.95 - 1.04 mm, C5 (APp3) 1.96 - 2.36 mm and C6 (APp4) 1.59 - 1.97 mm.

In the case of C5 and C6 points, a very large deviation from the set position was shown, and here the coordinates of the points will have to be corrected. In the case of a measuring cube with a side length of 1000 mm, additional measurements were made at the speed of movement of the robot limited to 10% and 50% of the maximum value, however, constant during individual tests. The purpose of this action was to check whether the limitation of the robot's travel speed limits

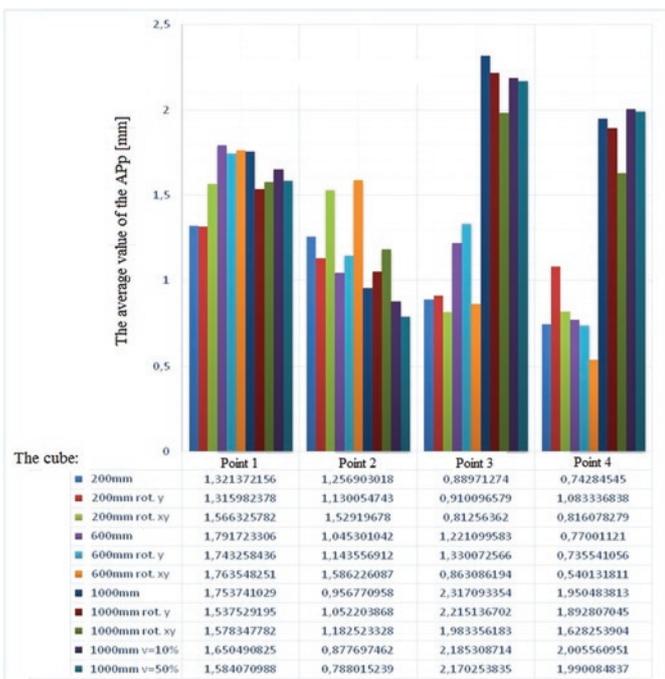


Fig. 8. The average values of robot positioning accuracy, for each paths, at individual measuring points

the deviation from the present position. The results of the test indicate the following positioning errors at individual points: C4 1.53 - 1.64 mm, C3 0.78 - 0.87 mm, C5 2.16 - 2.18 mm and C6 2 - 2.01 mm. On this basis, it can be stated that the change in the robot's speed does not have a significant effect on the difference in the value of deviations from the set position in individual tests. It was not noticed that the deviation values were clearly closer to zero as the robot's speed decreased in individual passes. The expected reduction in the positioning accuracy can be observed with the increase of the cube size and the complexity of the path only to cubes with sides of 200 and 600 mm. With larger dimensions of the measuring cube, the positioning accuracy of the robot is different in relation to the points of individual tracks and unpredictable. It is therefore necessary to take into account the occurrence of these errors, because they cannot be avoided, for example by means of program compensation.

### 5. Tests of repeatability of positioning

Reproducibility tests of the positioning of an industrial robot marked with the  $RP_i$  symbol were carried out in accordance with the guidelines of PN-EN 9283 [27]. The results were developed using data from positioning accuracy tests. Repeatability is defined as a sphere with a radius equal to the value of repeatability  $RP_i$  and a centre with coordinates calculated from the average coordinates of individual measurement points in accordance with the following relationships:

$$RP_i = \bar{I} + 3S_i, \tag{5}$$

where:

$$\bar{I} = \frac{1}{n} \sum_{j=1}^n I_j, \tag{6}$$

$$I_j = \sqrt{(x_j - \bar{x})^2 + (y_j - \bar{y})^2 + (z_j - \bar{z})^2}, \tag{7}$$

$$S_i = \sqrt{\frac{\sum_{j=1}^n (I_j - \bar{I})^2}{n-1}} \tag{8}$$

Fig. 9-11 show the selected results of calculating the repetition of the positioning of the considered robot, when reaching individual

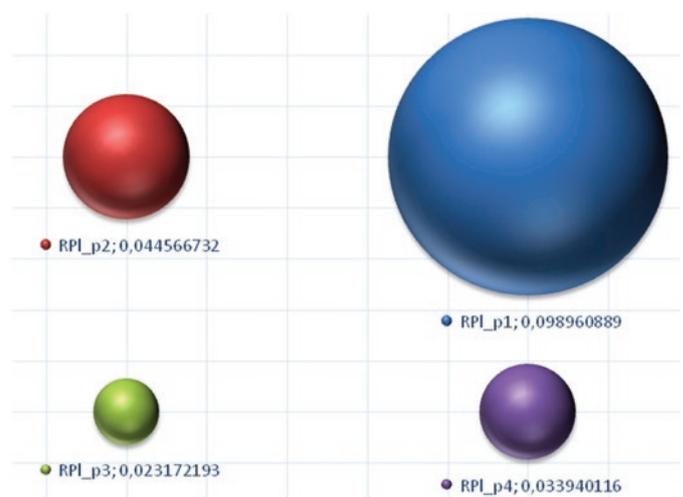


Fig. 9. Repeatability of positioning of the cube points with a side length of 200mm, with tool rotation +20° in X and Y axes

measurement points. The created spheres, in individual drawings, were scaled in relation to each other

Figure 12 summarizes the average results of the positioning repeatability test in four measurement points of cubes with sides' length of 200, 600 and 1000 mm.

In individual measurements, points were achieved:

- without tool rotation,
- with tool rotation by an angle of  $+20^\circ$  to the Y axis,
- with tool rotation by an angle of  $+20^\circ$  relative to the X and Y axes,
- in the case of a cube with a side length of 1000 mm, additionally without the rotation of the tool at speeds of 10% and 50% of the maximum speed.

The results of the positioning repeatability test for a cube with a side length of 200 mm show errors at individual points: C4  $0.12 \pm 0.03$  mm, C3  $0.055 \pm 0.015$  mm, C5  $0.035 \pm 0.015$  mm and C6  $0.04 \pm 0.01$  mm. It should be noted that the sphere at point C4 has a clearly larger radius in relation to the other spheres. The highest value of positioning repeatability, for each of the measurement points, was obtained in the test with tool rotation at axes X and Y. In the case of a cube with a side length of 600 mm, positioning errors were found at individual points: C4  $0.045 \pm 0.005$  mm, C3  $0.03 \pm 0.01$  mm, C5  $0.03 \pm 0.01$  mm and C6  $0.035 \pm 0.005$  mm. The determined spheres of repeatability of positioning for the measuring cube with side length 600 mm are more even than the measuring cube with side length 200 mm. In addition to the uniformity of measurements, it should also be noted that their small values indicate very good robot repeatability. In the case of cubes with a side length of 1000 mm, repeatability errors were found at individual points: C4  $0.055 \pm 0.015$  mm, C3  $0.055 \pm 0.015$  mm, C5  $0.075 \pm 0.035$  mm and C6  $0.08 \pm 0.04$  mm. Spheres have a large discrepancy between the values of repeatability at each of the measurement points. Therefore, it cannot be determined which of the points was achieved with the best reproducibility. As a result of the repeatability of positioning test with variable speed of travel, the following positioning repeat errors were shown in particular points: C4  $0.09 \pm 0.01$  mm, C3  $0.035 \pm 0.005$  mm, C5  $0.045 \pm 0.015$  mm and C6  $0.03 \pm 0.01$  mm. The results obtained during the tests with the reduced speed suggest that the low speed does not change the value of the positioning repeatability and it is not justified to reduce it to obtain better repeatability.

As it was observed, the robot positioning repeatability is varied at the measuring points of individual paths. On the basis of all tests, no specific trend of the robot's positioning repeatability can be demonstrated. In the case of the industrial robot under study, the obtained values of repeatability of positioning are not a significant problem when creating programs in offline mode, because the values of deviations are negligible in relation to the tasks for which the robot can be used (mainly welding).

## 6. Study of the mapping of the robot's motion path in real and virtual environments

The path mapping study aimed to determine how the movements of an industrial robot programmed in a virtual offline programming environment are reproduced in reality. For this purpose, the "TCP track" option was used in the Robcad program, by means of which it is possible to create points in the TCP location on the robot's motion path. To register the real robot's path, a Faro tracker was used. Due to the fact that the robot's movement did not follow the path perpendicular to the tracker, the probe had to be periodically moved towards the tracker (SMR viewing angle is  $30^\circ$ ). The robot's travel speed has been reduced to 150 mm/min. After the measurements, the coordinates of the points, measured by the Faro tracker, were copied to the Robcad program. For this purpose, a macro program of Microsoft Excel

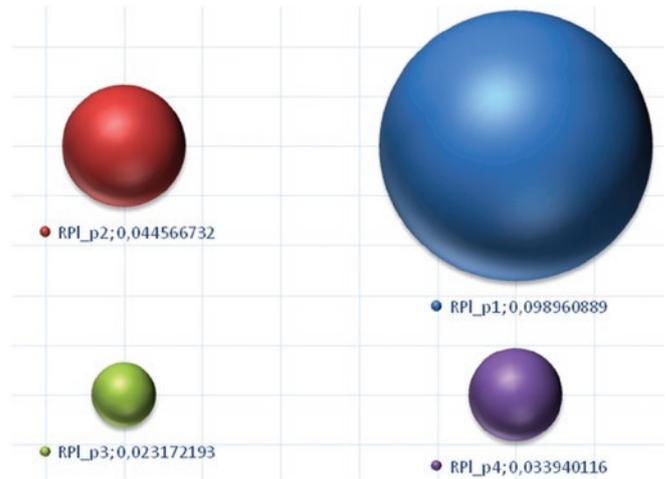


Fig. 10. Repeatability of positioning of the cube points with a side length of 600 mm, with tool rotation  $+20^\circ$  in X and Y axes

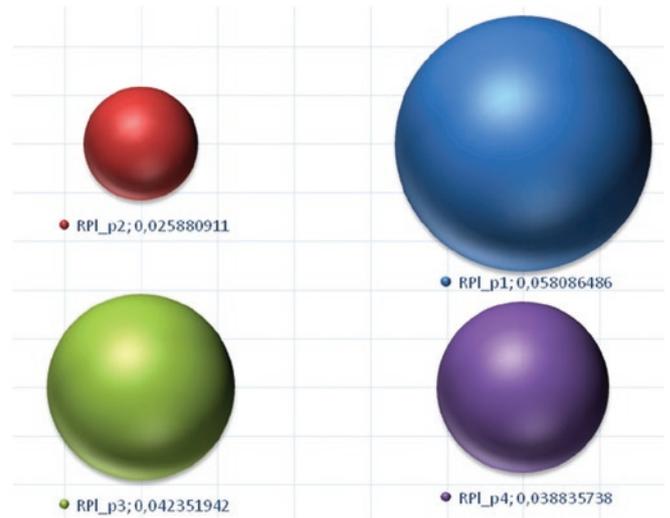


Fig. 11. Repeatability of positioning of the cube points with a side length of 1000 mm, with tool rotation  $+20^\circ$  in X and Y axes

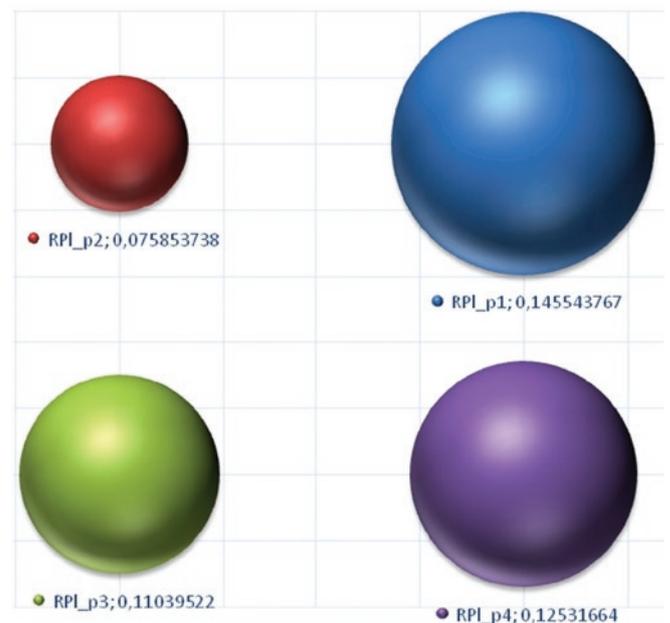


Fig. 12. The average values of the positioning repeatability  $RP_i$  of each track at individual measuring points

was used, which recorded reference measuring points spaced apart by 10 mm.

The real robot track recorded in this way was compared at the created reference points with the paths generated in the Robcad program. In the first case, the registered course of the real robot path was compared with the simulated path in the “default” mode (normally supplied with the Robcad program), in the second simulation the Robot Controller Software (RCS) “Kuka\_KRC1\_Spot” was used.

Fig. 13 graphically presents the differences between the course of obtained paths in one of the planes in the virtual environment in the “default” mode (violet colour) and with the RCS tool (yellow colour). Fig. 14 and 15 show the deviations in individual axes of the path simulated in a virtual environment relative to the path measured on the real robot, respectively in the case of simulation in the “default” mode (Fig. 14) and using the RCS Kuka\_KRC1\_Spot tool (Fig. 15). On the other hand, Fig. 16 shows a graphical comparison of paths created by the Robcad program and the paths of the real robot movement with tool rotation + 20° in the X and Y axes. It is clearly visible that the real path (blue) coincides with the path created using the RCS tool (yellow), but significantly differs from the path created in the “default” mode (violet colour).

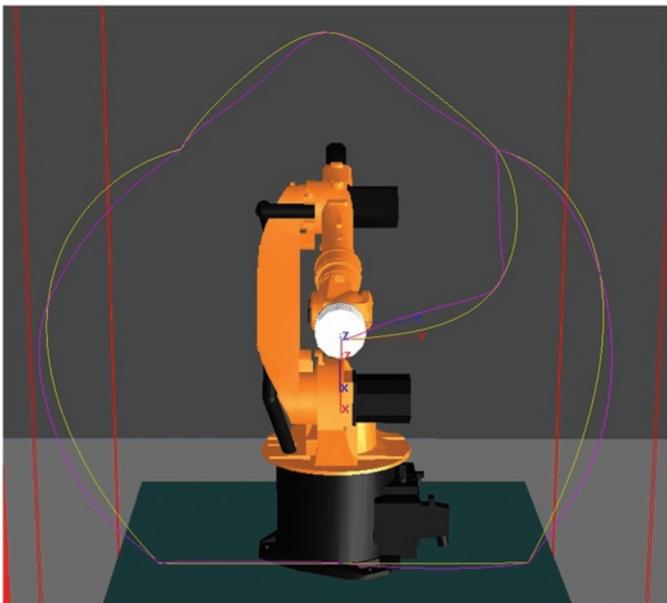


Fig. 13. Paths created by the Robcad program when moving from the Home position with the tool rotation + 20° in the X and Y axes: Violet colour - the path created in the “default” simulation mode, yellow - in the simulation mode with the RCS tool

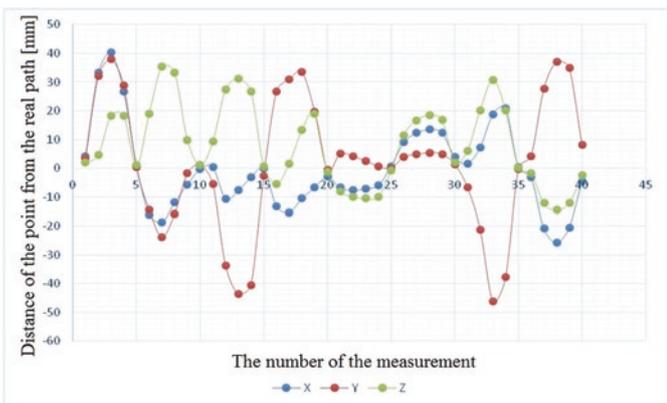


Fig. 14. Path deviation with tool rotation + 20° in X and Y axes in Robcad in “default” mode relative to the path measured by the Faro tracker

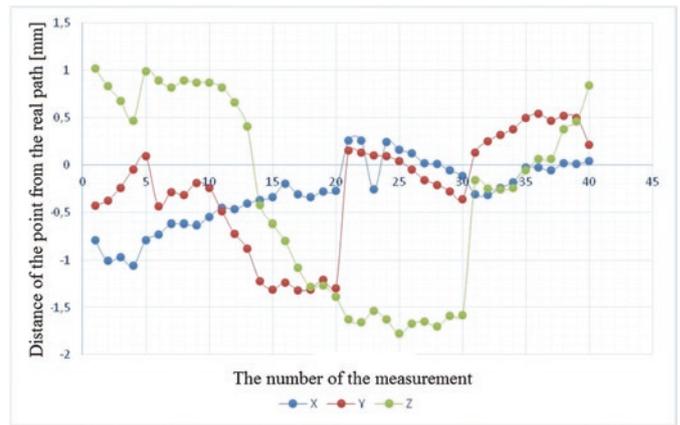


Fig. 15. Path deviation with tool rotation + 20° in X and Y axes in the Robcad program with the RCS Kuka\_KRC1\_Spot tool relative to the path measured by the Faro tracker

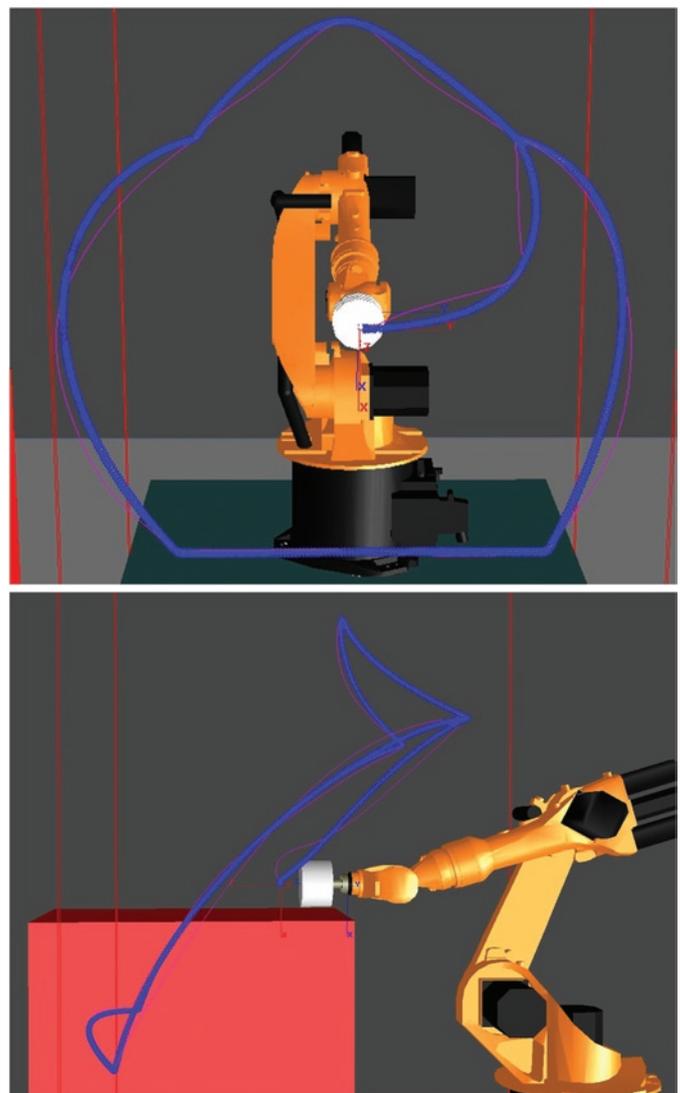


Fig. 16. Comparison of paths created by the program Robcad and the real path with the rotation of the tool + 20° in the X and Y axes. Paths: real - blue colour, simulated in the “default” mode - violet colour, simulated with the RCS tool - yellow colour

## 7. Summary

Programming robots in the offline environment depends to a large extent on the exact mapping of elements of their real environment as well as their distribution. Therefore, it is important that the measurements of objects in the real robot work environment are carried out carefully and accurately. It is also very important to determine the work object base and its TCP point. This task requires high precision. The experience and skills of the person responsible for the measurements play a key role in offline programming as well as the launch of the real robot.

When creating programs in the offline environment, it must also be taken into account some imperfections of the industrial robot, and therefore its accuracy and repeatability of positioning. As demonstrated during the tests, these are quantities that cannot be precisely predicted. The accuracy of modern industrial robots currently used in most production plants can be a significant problem for programmers. As it was shown, when measuring the accuracy of reaching the set measuring points, in the case of a cube with a side length of 1000 mm, one of the points was achieved with an error of 2.21 mm in relation to the set position. This value is unacceptable and needs to be corrected during online programming. It should be noted that this error will occur regardless of how well the program was prepared in the offline environment, or how accurately the robot's environment was measured and mapped in a virtual environment. Even the best-written offline program may turn out to be inadequate to the real world. It is extremely important that a person, who is responsible for programming a real robot in his work environment, verifies the points of his movement path, paying particular attention to those that are close to the elements of the environment or are process points in such opera-

tions, like gluing or welding. The introduced patch of the program developed offline will be maintained during the robot's work due to high repeatability, whose value in the worst case during the test was 0.15 mm. This ensures that the robot's position is achieved with the required precision.

An important element is also the use of appropriate software in the offline environment, because the real robot's motion paths can have serious deviations from programs created in this environment. This introduces a threat to the robotic cell equipment and can lead to collisions. The right software allows working offline, without worrying that the actual robot will move along paths significantly different than the robot in the simulation. When comparing the motion path of an industrial robot simulated in a 3D environment with real conditions, significant discrepancies were found when using standard software ("default" mode). They can be significantly reduced by using an additional Robot Controller Software tool offered for the Robcad system.

During the tests, the accuracy and repeatability of positioning of an industrial robot and precision of mapping of motion paths, developed during offline programming, by a real robot were verified. The presented measurement method also allows assessing the impact of such factors as its load or ambient temperature on these parameters of the robot's motion. This paper discusses the most important aspects of offline and online programming of industrial robots. In order to fully evaluate the precision of an industrial robot, one should also take into account additional parameters of its work, such as the mapping of rotation behaviour at process points, robot dynamics measurements, etc. These issues are the subject of further research and their results will be presented in subsequent works by the authors.

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